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SYMMETRY AND QED TESTS IN RARE ANNIHILATION MODES OF POSITRONIUM

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Recent experiments on positronium annihilation have confirmed QED calculations at high orders of α and tested discrete fundamental symmetries. These measurements search for rare modes of annihilation which are distinguished from backgrounds by their specific decay signatures. New developments in beyond Standard Model theory provide motivation for new measurements of such decays. A brief history of searches for rare annihilation modes of Ps is given. Recent experimental and theoretical developments are reviewed. Experiments currently being planned are discussed.

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1. Introduction – History and Reviews

Positronium (Ps), the atomic system of a positron and an electron, has been used in experiments on fundamental physics for more than half a century since its first observation in 1951 by Deutsch.¹ It sufficed at first to confirm the prediction of the bound state and its basic hydrogenic energy spectrum, but experiments have continued with many applications of the simplest chemical element. But unlike ordinary atoms, Ps is unstable against matter/antimatter annihilation. Experiments which detect the annihilation radiation produced by positronium now test fundamental physical theories. The connection from Ps annihilation to tests of fundamental physics depends strongly on the unusual symmetry properties of Ps. Like other atoms bound by a central potential, states of positronium are parity (**P**) eigenstates. Selection rules for the annihilation modes of Ps based on rotational and parity symmetry were discussed by several authors even before Ps had been definitely observed.² Positronium is also an eigenstate of the charge conjugation operator corresponding to particle/antiparticle interchange, **C**. Every particle/antiparticle bound state is an eigenstate of **C**, and uncharged fundamental particles (e.g. bosons) can be as well. In positronium, the **C** eigenvalue is $C_{Ps} = (-1)^{L+S}$, where L is the orbital and

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S the total spin angular momentum. The \mathbf{C} selection rule for allowed annihilation modes was derived³ almost concurrently with the first conclusive observation of positronium. The photon is intrinsically \mathbf{C} -odd, so the eigenvalue for an n -photon state is $C_\gamma = (-1)^n$. If charge conjugation symmetry is respected in the QED process of Ps annihilation, then positronium must decay to an even or odd number of photons such that $(-1)^{L+S} = (-1)^n$. Since states of Ps are eigenstates of \mathbf{C} and \mathbf{P} , Ps is a unique laboratory for testing the discrete fundamental symmetries \mathbf{C} , \mathbf{P} , and \mathbf{T} .

Loosely speaking, when the electron and positron in a Ps atom overlap, they annihilate. Studies of Ps annihilation use the two $N = 1$, $L = 0$ ground states in Ps, with total spin $S = 0$ (para-Ps) and $S = 1$ (ortho-Ps) (separated by the hyperfine splitting of 203.4 GHz). The lifetime against annihilation of p-Ps is approximately 125 ps (first estimated in reference 4), while the lifetime of o-Ps is approximately 140 ns (first calculated by Ore and Powell in reference 5 along with the three-photon spectrum). This discrepancy is a consequence of the selection rules for \mathbf{C} and \mathbf{P} , forbidding (o-Ps $\rightarrow 2\gamma$). The annihilation rate, Γ , can be naively factored as the product of an (e^+e^-) n -photon scattering cross section and the electron density at the positron's position:

$$\Gamma(\text{Ps}(J) \rightarrow n\gamma) = \frac{1}{2J+1} |\psi(0)|^2 (4v_{rel}\sigma_{scatt}(e^+e^- \rightarrow n\gamma))_{v_{rel} \rightarrow 0}, \quad (1)$$

where v_{rel} is the relative velocity of the e^+ and e^- . The electron density at the positron location is simply the square of the Ps wavefunction, ψ , at zero separation. All of the physics in the annihilation amplitude ($v\sigma$) and the rate Γ is governed by Quantum Electrodynamics. For the ground state ($N = 1$) of Ps, the wavefunction amplitude is $|\psi(0)|^2 = \frac{1}{8\pi} m^3 \alpha^3$, and for each of the n photons emitted, one power of α is added to the decay rate as one more photon vertex is added to a Feynman diagram. We naively expect that o-Ps, annihilating to three photons, has a decay rate smaller by a factor of α (and constants of order 1) than p-Ps. Of course, p-Ps can in principle annihilate to any even number of photons, and we see that the lowest-order decay rate for the process (p-Ps $\rightarrow 4\gamma$) is proportional to α^7 . Likewise, for o-Ps, (o-Ps $\rightarrow 5\gamma$) $\propto \alpha^8$.

The strict odd-even selection rule for Ps annihilation invited examination when discrete fundamental symmetries (\mathbf{P} and \mathbf{C}) were found to be violated. Early searches for \mathbf{C} violating decays of Ps were motivated by similar tests searching for $\pi^0 \rightarrow 3\gamma$ (which was in turn motivated by the observation of \mathbf{CP} violation in kaon decay.^a Schechter was the first to propose a \mathbf{C} violation test in the decay mode (p-Ps $\rightarrow 3\gamma$), suggesting that an experiment might use the fact that the phase space for such three-photon decays (under the assumption of Lorentz invariance) must differ strongly from the phase space for allowed (o-Ps $\rightarrow 3\gamma$).⁹ Distinguishing rare decays by their unique geometry continues to be a key technique in new searches.

^aSee references 6, 7, and 8 as early work with pion decay.

After early measurements to search for C -violation (Refs. 10 and 11), discrete fundamental symmetry studies on Ps annihilation lay dormant, until the era of the “orthopositronium lifetime problem.” When it appeared that there was a large discrepancy between QED calculations and measurements of $\Gamma(o - \text{Ps})$, attention turned to the possibility of exotic, unobserved decay modes of o-Ps. Unobserved decay modes could explain experimental results which found a shorter lifetime than that calculated by QED. Exotic modes from several new physics processes were suggested: new massive bosons, axions, single photon emission, anomalously large QED allowed contributions (*viz.* from o-Ps five-photon decay), C -odd “wrong” numbers of final state photons, or other “invisible” decays. To explain the lifetime problem, the branching ratio for o-Ps to decay by exotic modes would need to be roughly 10^{-3} of the usual three-photon decay. By 1993, however, searches for exotic decay modes to heal the breach between theory and experiment for $\Gamma(o - \text{Ps})$ had become stringent enough to reject all but the most *ad hoc* hypotheses of new physics.¹² Furthermore, in 1995, Escribano *et al.* showed that even if there were such exotic decay modes of Ps, they would generate physics which would be in stark conflict with the current satisfactory understanding of primordial nucleosynthesis.¹³ Extra, exotic couplings of e^+ , e^- , and γ would provide extra degrees of freedom for the components of nuclei in the early universe.

Newer experiments have measured rare decay modes to provide tests of QED at high orders of α (Section 3). New theoretical ideas for Beyond Standard Model physics provide motivation for work on rare decays of Ps, and experiments continue to extend their sensitivity to exotic rare decay modes (Section 4).

1.1. Other reviews

Because of the maturity of the field, several review articles have surveyed tests of fundamental physics with Ps annihilation. Reviews from 1993 (Refs. 14 and 12) summarized the status of QED calculations and the “orthopositronium lifetime problem” at that time. A thorough treatment of that issue appears in Ref. 15.^b Older reviews by experimentalists include References 17 and 18. Reference 19 emphasized theoretical developments. More recent reviews of rare decays of Ps include Refs. 20 and 21. Karshenboim recently reviewed bound-state QED calculations in Ps and experimental results, making comparisons to QED tests in other bound systems.²² Reference 23 is an excellent summary of early theoretical and experimental work on e^+ and Ps.

^bThe “orthopositronium lifetime problem” has been declared solved (“Resolution of the Orthopositronium-Lifetime Puzzle”¹⁶) by the group most intimately involved in the experimental side of the problem. In short, the discrepancy between the results by the Michigan group (gas and vacuum measurements) for $\Gamma(o - \text{Ps})$ and theory was caused by incomplete understanding of the thermalization of the o-Ps sample.

2. Producing Ps for annihilation experiments

Rare annihilation experiments typically use radioactive isotopes as a primary source of positrons, which are then moderated and stopped to form Ps. The most convenient sources (because of their long half-lives) are ^{22}Na ($\tau_{1/2} = 2.2$ year, $E_0 = 0.54$ MeV) and $^{68}\text{Ge}/^{68}\text{Ga}$ ($\tau_{1/2} = 288$ days, $E_0 = 1.90$ MeV). Some groups have constructed low-energy (few keV) positron beams based on either long-lived radioisotopes or short-lived positron emitters produced by an accelerator. When Ps is formed from low energy positrons which capture electrons from materials, both o-Ps and p-Ps are formed in a statistical ensemble. Ps may be produced efficiently by the well-known technique of stopping positrons in an insulator with extremely small (μm to nm) grain size. The populations of o-Ps and p-Ps in an experiment may be separated by measuring the time of the annihilation after positron emission. The positron emission time may be determined by detecting the energetic positron, a gamma ray from an excited daughter state, or by ionization produced by energetic beam positrons impinging on an electron emission surface. The populations of o-Ps and p-Ps are often imperfectly isolated, however. If p-Ps is to be studied, then if e^+ are injected into a Ps forming medium, some o-Ps annihilations occur immediately. Free e^+e^- annihilation (rather than bound-state Ps annihilation) may be observed by injecting positrons into a material in which Ps formation is forbidden (e.g. a metal). Although this annihilation is predominantly by two-photon emission, there is a small contribution of three-photon annihilation events (from P-wave e^+e^- interactions). On the other hand, in materials in which o-Ps is formed copiously, there are always impurities which result in “pickoff” annihilation, in which o-Ps encounters a bound electron and the positron then annihilates with this electron in a relative spin singlet collision. This results in two-photon annihilation signals at long times. Careful measures must be taken to minimize or quantify the pickoff effect, particularly in the measurements of $\Gamma(\text{o-Ps})$. There is also the unavoidable practical difficulty of “accidental” event contamination of o-Ps and p-Ps samples, in which a start time signal of positron emission from one decay event becomes associated with the decay annihilation of a different Ps atom. Experiments to search for rare decay modes often use high source activities to minimize total counting time, so such effects must be accounted for.

3. QED tests

3.1. ($p\text{-Ps} \rightarrow 4\gamma$)

The annihilation of p-Ps to four photons can be characterized by the branching ratio $R_4 \equiv \frac{\Gamma(p\text{-Ps} \rightarrow 4\gamma)}{\Gamma(p\text{-Ps} \rightarrow 2\gamma)}$, the probability that p-Ps annihilates to four photons instead of two. Calculations of this branching ratio to lowest order have been performed by several groups (Refs. 24, 25, 26, 27, 28). These calculations

agree, and the most precise (Ref. 28) gave $\Gamma_{\text{LO}}(4\gamma) = 0.013893(6)m\alpha^7$.^c The one-loop (order α) correction to the four-photon decay rate was calculated to be $\Gamma(4\gamma) = \Gamma_{\text{LO}}(4\gamma) [1 - 14.5(6)\frac{\alpha}{\pi} + O(\alpha^2)]$, a 3.4% downward correction, yielding $R_4 = 1.4388(21) \times 10^{-6}$.³⁰ There have been five measurements of R_4 . These are shown in Figure 3.1 compared with the calculation at lowest order and to the calculation with one-loop corrections. The first-order correction to $\Gamma(4\gamma)$ clearly improves

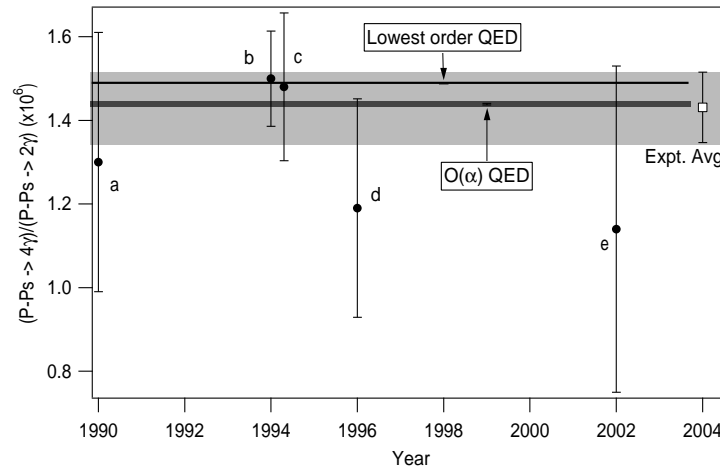


Fig. 1. Measurements of the p-Ps branching ratio, R_4 . References are a: 29, b: 31, c: 32, d: 33, and e: 34. For these measurements, $\chi^2 = 0.507$, and the average is $R_4 = 1.431(84) \times 10^{-6}$.

agreement with the experiments, which are consistent. This represents agreement between QED theory and measurement at order α^8 , the highest order of the coupling constant ever tested. The most precise measurement of R_4 was performed using the Crystal Ball NaI detector array, located at Heidelberg-Darmstadt.³¹ This experiment (and the one in Ref. 32) was a dedicated search for four-photon annihilation of p-Ps: the source was ^{22}Na enclosed within an aluminum shell. The formation of o-Ps is greatly suppressed in conductors. This suppressed the three-photon annihilation rate, which could produce four-photon background events in the data by scattering of one photon.

3.2. (*o*-Ps \rightarrow 5 γ)

At the same time that $\Gamma(4\gamma)$ was being calculated, similar calculations for $\Gamma(o\text{-Ps} \rightarrow 5\gamma)$ were being performed. The first calculations found $\Gamma(5\gamma) = \Gamma_{\text{LO}}(3\gamma) [0.0189(11)\alpha^2]$ (Ref. 26) and $\Gamma(5\gamma) = \Gamma_{\text{LO}}(3\gamma) [0.0181\alpha^2]$ (Ref. 27). The

^cThis calculation was performed in conjunction with the measurement of Ref. 29 and used software to evaluate the tree-level Feynman diagram for (p-Ps \rightarrow 4 γ).

most precise calculation of the lowest-order five-photon decay rate is $\Gamma(5\gamma) = \Gamma_{\text{LO}}(3\gamma) [0.018127(15)\alpha^2]$ (Ref. 35).^d Since the lowest order rate for three photon decay is $\Gamma(3\gamma) = \frac{2}{9\pi}(\pi^2 - 9)m\alpha^6$, the five-photon rate at lowest order is proportional to α^8 . The result from Matsumoto *et al.* in Ref. 35 implies a branching ratio $R_5 \equiv \frac{\Gamma(o\text{-Ps} \rightarrow 5\gamma)}{\Gamma(o\text{-Ps} \rightarrow 3\gamma)} = 0.9591(8) \times 10^{-6}$. To date, no calculations of the first order corrections have been performed. The five-photon branching ratio has been measured twice. Matsumoto *et al.*³⁵ found $R_5 = (2.2_{-1.6}^{+2.6} \pm 0.5) \times 10^{-6}$, based on a single observed event, and Vetter and Freedman found $R_5 = 1.67(99)(37) \times 10^{-6}$, with three events.³⁴ Both experiments are consistent with the tree-level calculations, although they seem to suggest a somewhat larger branching ratio. These measurements imply agreement with QED at eight orders of the coupling constant and five external photon lines. The Tokyo Metropolitan University group reports in Ref. 36 that it is improving the Ps source in its UNI array and could achieve a sample of thirty five-photon decay events. With a statistical uncertainty in R_5 of 18%, it may be worth the effort to calculate the one-loop corrections to $\Gamma(o - \text{Ps} \rightarrow 5\gamma)$. The process $(p\text{-Ps} \rightarrow 6\gamma)$, if it has a branching ratio of (naively) 10^{-12} , would require heroic, perhaps impossible, experimental effort to observe. The measurement of Matsumoto *et al.* had an acquisition time of ≈ 230 days, while the measurement by Vetter and Freedman had an acquisition time of ≈ 11 days, and the six photon decay mode would be more rare in the data by roughly a factor of one million. Evaluating possible background contributions in this case would be extremely difficult.

4. Tests of discrete fundamental symmetries

4.1. C-Violation

The first experiment on **C** symmetry in Ps annihilation was reported by Mills and Berko, who searched for decays of para-positronium into three photons.¹⁰ They were aware that the allowed phase space for photons produced in **C**-violating decays must be different from those emitted in the usual **C**-conserving processes. They exploited this in designing their detector apparatus – the signal was to be a change in the detected rate of three-photon events, depending on the event topology, as the fraction of o-Ps and p-Ps in the source was changed. Mills and Berko used a planar array of NaI gamma-ray counters, placed to detect three types of events: back-to-back gamma ray hits (two photon p-Ps decay), three photon hits in a symmetric pattern (angles between photons $(120^\circ, 120^\circ, 120^\circ)$), and three photon hits in an asymmetric pattern: $(90^\circ, 120^\circ, 150^\circ)$. An ortho-positronium source was inserted in the detector array, and they measured the ratio of counts with symmetric to asymmetric geometries for three-photon events. They then added quenching gas to their Ps source, which greatly reduced the amount of o-Ps formed in their source by the pickoff process: essentially all of the Ps formed would now be p-Ps. But the

^dagain performed using Standard Model Feynman diagram software in conjunction with the measurement of $(o\text{-Ps} \rightarrow 5\gamma)$ in Ref. 35.

C-odd process ($p\text{-Ps} \rightarrow 3\gamma$) would have much different phase space for the emitted photons (based on a spin argument). If ($p\text{-Ps} \rightarrow 3\gamma$) occurred, it would increase the number of asymmetric events. This experiment set a limit of $R_3^{\mathcal{O}} \equiv \frac{\Gamma(p\text{-Ps} \rightarrow 3\gamma)}{\Gamma(p\text{-Ps} \rightarrow 2\gamma)} \leq 2.8 \times 10^{-6}$. This approach was limited by high backgrounds and the “difference of two large numbers” problem, and this search for $R_3^{\mathcal{O}}$ has not been repeated.

It is important to note that the limit for $R_3^{\mathcal{O}}$ is model-dependent. In an experiment which searches for high-multiplicity gamma ray events of either **C**-allowed or **C**-forbidden annihilation, the number of observed events must be translated to a branching ratio to compare to the usual decay rate. For example the branching ratio for the **C**-odd ($o\text{-Ps} \rightarrow 4\gamma$) is derived from measured quantities in an experiment by

$$R_4^{\mathcal{O}} = \frac{[N(4, \text{long}) - B(4, \text{long})] \varepsilon(3\gamma)}{N(3, \text{long}) \varepsilon(4\gamma)}, \quad (2)$$

Here, $N(4, \text{long})$ corresponds to the number of observed four-photon events occurring at late times (and thus from $o\text{-Ps}$ decay), while $B(4, \text{long})$ is the number of background counts expected from all sources. It is safe to assume that the number of three-photon background events is negligible. The efficiency of the detector array to observe a **C** violating annihilation event, $\varepsilon(4\gamma)$ must be known. This efficiency depends strongly on the detector and source geometry. It is affected by energy acceptance windows, detector and source sizes, and shielding. In recent experiments, the detection efficiency for high-fold annihilation events ($n_\gamma > 3$) is derived from detector simulations. Monte-Carlo generated annihilation events with a particular distribution in phase space (allowed combinations of photon momenta) are run through gamma-ray energy transport software to simulate energy deposition in the detector elements. The allowed phase-space distribution of photons for four and five photon decay modes depends on the structure of the photon propagator and Jacobean in QED calculations, and is encoded in software to generate randomized events consistent with the allowed phase space.^e Because **C**-violating annihilations must have different phase space distributions from the QED-allowed decays, the calculated detector efficiency differs from the allowed decays, and is model-dependent. In the experiment by Mills and Berko, a specific **C**-violating, Lorentz-invariant Lagrangian was assumed and guided the experiment design. Note that the efficiency for detecting the allowed decay mode, $\varepsilon(3\gamma)$, may be determined by measurements of the Ps source activity referenced to other emissions and detectors (e.g. by counting 1275 keV gammas from a ^{22}Na source and measurements to determine the $o\text{-Ps}$ formation fraction).

^eFor three-photon decay, a closed form for the energy and angular distributions of the photons may be derived from the Ore-Powell calculations.

4.1.1. (*o*-Ps $\rightarrow 4\gamma$)

The most thoroughly searched **C**-violating decay mode is (*o*-Ps $\rightarrow 4\gamma$), limiting the **C**-odd branching ratio $R_4^{\mathcal{O}} \equiv \frac{\Gamma(\text{o-Ps} \rightarrow 4\gamma)}{\Gamma(\text{o-Ps} \rightarrow 3\gamma)}$. From an experimental point of view, this is perhaps the simplest **C**-violating decay mode search. A sample of Ps is generated, and the p-Ps fraction is allowed to decay away over a few ns, leaving only the o-Ps component. In this case, one background for the desired four-photon decays is minimized – the QED-allowed (p-Ps $\rightarrow 4\gamma$) decay is reduced if the (o-Ps \rightarrow p-Ps) pickoff rate is minimized. On the other hand, searching for the **C**-violating decay (p-Ps $\rightarrow 3\gamma$) is susceptible to backgrounds from (o-Ps $\rightarrow 3\gamma$) decays generated by the source. References 11 and 37 are the first searches for the (o-Ps $\rightarrow 4\gamma$) decay mode. They found no excess events and established the limit (1σ) of $R_4^{\mathcal{O}} < 8 \times 10^{-6}$. This experiment used four detectors arranged in a tetrahedral geometry, again arguing that this geometry was particularly sensitive to **C**-violating four-photon decays which preserve Lorentz invariance.

The next experiments to search for $R_4^{\mathcal{O}}$ were performed in conjunction with measurements of the allowed four and five-photon decay modes. The group at Tokyo Metropolitan University, using a dedicated array (nicknamed UNI) of 32 NaI detectors and collimators, improved the limit for $R_4^{\mathcal{O}} < 2.6 \times 10^{-6}$ (90% C.L.).³³ The most recent search for **C** violating events, at Lawrence Berkeley National Laboratory, used the Gammasphere array of Compton-suppressed high-purity germanium detectors, again in conjunction with a measurement of the allowed four and five-photon decay modes. This experiment found a limit $R_4^{\mathcal{O}} < 3.7 \times 10^{-6}$, and also a limit for the decay mode (p-Ps $\rightarrow 5\gamma$), finding $R_5^{\mathcal{O}} < 2.7 \times 10^{-7}$. This is the smallest limit for an exotic branching ratio of Ps, but it may be specious. It seems unlikely that any tenable theory would predict a **C**-odd decay of (p-Ps $\rightarrow 5\gamma$) while not allowing other **C**-violating behavior (evading other limits), by virtue of cancellations at lower orders of α .

All of these experiments assumed that the detection efficiency of **C**-violating four-photon events in the arrays was equal to the detection efficiency for QED-allowed decay events. This assumption should be more valid for arrays with better angular resolution, as there is a lower probability for events with unique geometry to contribute to the overall efficiency (i.e. the four-detector tetrahedral array of Mills and Rich had an efficiency of approximately zero for allowed four photon decays).

All of the experiments on four and five-photon decay since Adachi²⁹ share certain features. The UNI array at Tokyo Metropolitan University, the Crystal Ball at Heidelberg, and the Gammasphere at Berkeley are all 4π arrays with high granularity. This provides maximum detection efficiency for high-fold events and suppresses scattered photon backgrounds, which would be worse with detector segments with large solid angles. In these experiments, detector simulations were crucial. Monte-Carlo routines generated randomized events from the phase space distribution of the QED-allowed four and five-photon decays. Simulated decay photons were propagated through energy transport routines (based on GEANT) which contained the

detector geometry. Such simulations not only determined the detection efficiency for four and five-photon events, but also estimated background processes, optimized data cuts, and tested systematic errors.

In the experiment by Yang *et al.*, the total acquisition time was ≈ 230 days. Three potential ($\text{o-Ps} \rightarrow 4\gamma$) events were detected with an estimated background of 3.4 events, and the detection efficiency for a ($\text{p-Ps} \rightarrow 4\gamma$) event was $\varepsilon(4\gamma) = 3.3 \times 10^{-5}$.³³ In the experiment by Vetter and Freedman using Gammasphere, the acquisition time was ≈ 11 days, and four potential ($\text{o-Ps} \rightarrow 4\gamma$) events were detected, with an estimated background of 3.75 events. The detection efficiency for a ($\text{p-Ps} \rightarrow 4\gamma$) event was $\varepsilon(4\gamma) = 1.6 \times 10^{-4}$.³⁴ For comparison, the Heidelberg Crystal Ball experiment to measure ($\text{p-Ps} \rightarrow 4\gamma$) had an acquisition time of 20 days and counted 406 ($\text{p-Ps} \rightarrow 4\gamma$) candidate events with a background of about 10 events. In this experiment (Ref. 31) $\varepsilon(4\gamma) = 4.3 \times 10^{-3}$. Note, however, that this experiment used a source which produced an o-Ps fraction of only 3×10^{-3} of the total positron annihilation rate. In searches for rare decays, background contamination in the data is obviously an issue. The first investigation by Mani and Rich on the ($\text{o-Ps} \rightarrow 4\gamma$) decay discussed types of backgrounds subdivided into coincident photon events and accidental photon events.¹¹ The treatment of backgrounds is more sophisticated in Adachi *et al.*²⁹, including a tabulation of some 29 different types of gamma-ray summing to produce events which cannot be distinguished from real four-photon decays. Both the Crystal Ball and UNI arrays used internal lead collimator systems to suppress detection of events in which gamma rays deposit partial energy in one detector module, and scatter into another. The Gammasphere array has bismuth germanate scintillator surrounding each germanium module which can reject some types of scattered events, but the better energy and angular resolution of the germanium detectors in Gammasphere allowed more stringent geometric selection of candidate events.

In Ref. 29, the largest sources of background are extra photons emitted during the β^+ emission from the source (^{68}Ge): bremsstrahlung photons emitted during the positron moderation process and photons from a transition in the daughter isotope. Other significant backgrounds (at long times after positron emission, when the events are predominantly o-Ps decay) come from Compton scattering of annihilation photons from two separate annihilation events. To minimize these sources of background, the Tokyo Metropolitan University group intends to use a system to displace the radioactive source from the center of the detector array and magnetically guides positrons towards the o-Ps forming medium at the center.³⁶ This minimizes material (and hence Compton scattering) at the center of the array, and removes daughter transition gamma rays from direct view of the detectors.

Theories of Beyond Standard Model physics provide new motivation for further searches for C-violating decay modes. Such theories seek to address well-known deficiencies of the Standard Model (e.g. gauge hierarchy and quantum gravity). One class of models is string/brane theory. Low-energy limits of string theories can imply non-commutative effective field theories. Non-commutativity is intimately related to

local Lorentz invariance violation.^f In non-commutative extensions of QED, direct photon-photon vertex couplings are allowed which do not preserve photon number. This destroys the usual odd-even selection rule for Ps decay, and would result (in lowest order) in the decay mode (p-Ps $\rightarrow 3\gamma$), with a three-photon energy spectrum distinct from the Ore-Powell o-Ps spectrum.³⁸

4.1.2. (o-Ps $\rightarrow 2\gamma$)

The decay mode (o-Ps $\rightarrow 2\gamma$) (which violates angular momentum conservation and hence violates Lorentz invariance as well as **C**) was searched for by the Michigan Ps group.³⁹ The experiment by researchers at the University of Tokyo⁴⁰ to look for decays to a neutral boson (o-Ps $\rightarrow \gamma + X^0$) can also be interpreted as a search for (o-Ps $\rightarrow 2\gamma$). The search for spatial anisotropy by Mills and Zuckerman was described as a search for this decay mode as well, but the search was not specific to this decay mode and searched only for a diurnal variation in the usual (o-Ps $\rightarrow 3\gamma$) rate. The result of the Michigan experiment was a limit $R_2^{\mathcal{O}} \equiv \frac{\Gamma(\text{o-Ps} \rightarrow 2\gamma)}{\Gamma(\text{o-Ps} \rightarrow 3\gamma)} \leq 2.23 \times 10^{-4}$.³⁹ The experiment used the same basic apparatus for the o-Ps lifetime measurement, and measured the energy spectrum of the (long-lived) o-Ps annihilation gamma rays. Gidley *et al.* searched for a peak in the energy spectrum at 511 keV, finding no excess counts at the endpoint. This experiment was background limited, as the search was for excess counts at 511 keV on the continuous (o-Ps $\rightarrow 3\gamma$) energy spectrum, which is steeply decreasing at 511 keV. Improving this search would require exquisite understanding of the energy response of the gamma-ray detector.

4.2. *T* or *CPT* violation

CPT-odd observables have been suggested as useful experimental signatures of new physics.⁴¹ A theoretical framework for describing *CPT* or Lorentz violating effects was suggested in Refs. 41 and 42, using parameters for an effective QED-like model which is a low-energy limit to some (unknown) Standard Model extension. Reference 43 pointed out that few predictions of the effective QED model for scattering or decay processes (such as Ps) have been tested, since most low-energy searches for *CPT* or Lorentz violating observables focus on comparative matter/antimatter properties and high precision tests of Local Lorentz Invariance in QED. Theoretical implications of the *CPT*-odd triple correlation in the decay of polarized o-Ps:

$$\vec{s} \cdot (\vec{k}_1 \times \vec{k}_2) \quad (3)$$

were studied in Ref. 44, and three experiments (Ref. 45, 46, 47) have searched for such a correlation. However, a reappraisal of positronium observables within the new effective QED formalism (similar to an analysis in Ref. 38) seems desirable. Interest

^fin simple terms because coordinate operators do not commute, meaning that some spatial directions are preferred.

in *CPT* violating theories motivated the Berkeley Gammasphere experiment on *CPT*⁴⁷, and a new effort on *CP*-violation by a positronium group in Zurich.⁴⁸

In Equation 3, \vec{s} is the spin vector of the ortho-positronium, and \vec{k}_1 and \vec{k}_2 are the momenta of the two most energetic annihilation photons. The quantity $(\vec{k}_1 \times \vec{k}_2)$ defines a vector normal to the decay plane. The *CPT*-odd correlation is an up/down asymmetry of decay planes with respect to the spin direction of the o-Ps. Two experiments searched for this decay correlation at a level of about 2% of the total decay rate by searching for an up-down asymmetry in planar arrays of sodium iodide decay photon detectors as the spin direction of an o-Ps source is reversed.^{45,46} These experiments searched for an amplitude C_A of the decay observable $\vec{s} \cdot (\vec{k}_1 \times \vec{k}_2)$ in the otherwise symmetric distribution of annihilation. These experiments detected the most energetic photon γ_1 in one detector, and searched for an asymmetry between two detectors in the count rate of the second most energetic photon γ_2 . Labelling the detectors up and down, these experiments measured the asymmetry $A = (N_{up} - N_{down}) / (N_{up} + N_{down})$. If the average polarization of the o-Ps was $\langle P \rangle$, then the angular correlation between spin and decay plane (C_A) is derived from the measured count asymmetry by $C_A = A / \langle P \rangle$. The detector geometry of these experiments determines the sensitivity to the correlation (3). In the Gammasphere experiment (Ref. 47), all three annihilation photons γ_1 , γ_2 , and γ_3 were detected, and the decay plane reconstructed to calculate its orientation with respect to the initial spin axis. Because any of the detectors in the array could detect any of the three photons, and because it could detect decay planes at any orientation with respect to the spin (rather than merely parallel or antiparallel), this experiment was less sensitive to geometric asymmetries of the counter arrangement or Ps source, or to unequal detector efficiencies. Reference 47 improved the limit on the correlation in Eqn. 3 to $C_A < 3 \times 10^{-3}$ (1σ).

Another observable suggested in Ref. 44 is *CP*-odd:

$$(\vec{s} \cdot \vec{k}_1) (\vec{s} \cdot \vec{k}_1 \times \vec{k}_2). \quad (4)$$

To search for this decay mode, aligned o-Ps must be used. An experiment by the Michigan group used a Ps source in a magnetic field and an array of three NaI detectors, setting a limit for a *CP*-odd decay amplitude $C_{CP} < 1.5\%$ (1σ).⁴⁹ Once again, the experiment design was guided by the different phase space for a particular decay mode. In a proposal by the group at Zurich to search for the correlation of Eq. 4, the apparatus described in Ref. 50 (previously used to search for “missing energy” decay modes to invisible particles plus one photon) will be used, and the sensitivity could be as much as one hundred times better.⁴⁸ The improvement would primarily be due to using a segmented 4π array.

4.3. Local Lorentz Invariance

As with many atomic systems which have been extensively studied experimentally, observing the decay of o-Ps has been raised to a high art, spawning entire fields

of applied physics. When such a well-developed experimental field exists, attention often turns to tests of local Lorentz invariance by searching for shifts in observed signals as a function of time or spatial orientation as the laboratory moves with respect to the fixed stars. There has been one search for Lorentz invariance violation in ($\text{o-Ps} \rightarrow 3\gamma$), motivated by the ortho-positronium lifetime puzzle.⁵¹ This was a relatively simple experiment which could be improved. Further theoretical work (based on effective QED or other Beyond Standard Model theory) to suggest possible signal ranges would be useful.

4.4. Searches for missing energy in Ps decay

Perhaps the most exotic decay mode for Ps decay would be decay to produce no radiation whatsoever. Loosely speaking, several potential decay mechanisms can be grouped together as “invisible”: decay to light axions, new very weakly-interacting bosons, or gravitons. Even these strange processes have analogous decays allowed in QED. If a positron annihilates with a bound electron, there is a possibility that the annihilation energy of 1.022 MeV will liberate an energetic electron from a bound state in a process similar to internal conversion. Such processes can result in a single gamma ray plus an energetic electron, or no gamma rays and an energetic electron in the final state. Momentum conservation is preserved by the recoiling ionized atom. Although there is some disagreement in the theoretical approach to such processes, recent QED calculations of these processes have been performed.^{52,53,54} These calculations agree on the very strong dependence of single-photon or no-photon annihilation rates on the atomic number of the annihilation medium. The Standard Model also allows o-Ps annihilation to neutrinos, which are practically invisible. This has been estimated to be $R_{\nu\bar{\nu}} \equiv \frac{\Gamma(\text{o-Ps} \rightarrow \nu\bar{\nu})}{\Gamma(\text{o-Ps} \rightarrow 3\gamma)} \approx 6.2 \times 10^{-18}$.^{55,56}

The Moscow experiment by Atoyan *et al.* is a good example of “missing energy” experiments.⁵⁷ In this experiment, an o-Ps source was placed inside the well of a calorimetric NaI detector. A positron was detected with a gas proportional counter after emission by a ^{22}Na source. The 1275 keV gamma ray was also detected in a supplemental NaI counter. This step reduced the sensitivity to “dark current” noise counts in the positron detector to provide a clean trigger for the calorimeter. After the trigger signal was applied, the total annihilation energy deposited in the calorimeter was measured. Candidate events are ones in which zero energy (or in principle, energy less than 1.022 MeV) was detected during the o-Ps lifetime. This experiment found $\frac{\Gamma(\text{o-Ps} \rightarrow \text{nothing})}{\Gamma(\text{o-Ps} \rightarrow 3\gamma)} < 5.8 \times 10^{-4}$ (90% C.L.), which was restrictive enough to exclude such decays as a resolution of the orthopositronium lifetime puzzle. The experiment of Mitsui *et al.* achieved the 10^{-6} level of sensitivity using a large mass (≈ 850 kg) of NaI and CsI scintillators, a source activity of $0.1 \mu\text{Ci}$ of ^{22}Na and an acquisition time of $\approx 9 \times 10^6$ seconds.⁵⁸

With the interest in string theories containing extra dimensions, it has been suggested in Ref. 21 that invisible decays of o-Ps could be a consequence of Randall-Sundrum extra dimensions. Gninenko *et al.* discuss how “invisible decays” of o-Ps

into extra dimensions proceed via virtual photons coupling to scalar particles, which then propagate onto the extra dimensions. The branching ratio for such decays is estimated to be proportional to the ratio of the o-Ps mass to a large energy scale characterizing the new physics (≈ 10 TeV). This energy scale is bounded by some experimental results, and also bounded by a triviality requirement: if the energy scale is too high, then the Randall-Sundrum extra dimensions do not address the gauge hierarchy issue in the Standard Model. This means that the branching ratio of o-Ps into extra dimensions is bounded from above and below.

$$O(10^{-10}) \leq \text{B.R.}(\text{o-Ps} \rightarrow \text{extra dimensions}) \leq 4 \times 10^{-9}. \quad (5)$$

How might an (o-Ps \rightarrow “nothing”) experiment reach such a sensitivity? Scaling up the Mitsui *et al.* result to longer acquisition times is not feasible. Faster counting rates and positron sources with higher activity are required to reduce the total counting time to a manageable level. Organic scintillators offer a much faster time response than high-Z inorganic crystals, so that a reasonable detector geometry would be a large volume of liquid organic scintillator, similar to the designs of the MiniBooNE⁵⁹ or KamLAND⁶⁰ neutrino oscillation experiments. Such a detector would require a three meter diameter in order to have negligible probability for two 511 keV photons to each leave less than ≈ 100 keV of energy in the detector volume. The total mass of such a volume of liquid scintillator would be roughly 10^5 kg. Such a geometry naturally addresses the hermeticity requirement, but the sacrifice in compactness compared to an array of high-Z inorganic solid scintillators is clear. However, there is now substantial experience with such detectors.

In such an experiment, the greatest challenge is to provide a clean trigger signal. Using a source of ^{22}Na (in which the trigger would be the detection of a positron passing through a thin plastic scintillator, followed by detection of the 1275 keV photon in the main detector) would be risky. The probability that the 1275 keV photon would Compton scatter in a positron detector or positronium moderator material, providing a false trigger, followed by deposition in the main detector volume of roughly 1 MeV seems to be about 10^{-7} . The energy resolution for a large liquid scintillator detector at 1 MeV (assuming 20% photomultiplier tube cathode coverage, similar to KamLand and MiniBOOne) is roughly 15%. This is not sufficient to discriminate against such events. If a ^{22}Na source is to be used, a high resolution element in the detector could select only photopeak trigger 1275 keV photons within a narrow energy window. One pitfall in using a radioactive β^+ source is the unavoidable electron capture decay. This can be accompanied by internal bremsstrahlung photon emission from the captured electron, and the spectrum of such photons extends to high energies ($E_0 + 1.022$ MeV). These photons can Compton scatter to form energetic electrons, which could be mistaken for positrons in any detector element. Such events would contribute to an “invisible” signal in this proposed detector at a branching ratio of $\approx 10^{-6}$, far short of the desired sensitivity. Several options could reduce this false trigger rate. The first is to use a radioisotope positron source in which decay to an excited state via electron capture (and hence

positronless decay) is greatly suppressed. Several short-lived light isotopes might be useful, but this would require a production accelerator close to the detector. Another possibility would be to guide an extremely clean positron beam into such a calorimeter, sacrificing some detector hermeticity. This concept is being pursued by the positron group at ETH, Zurich.⁶¹

As for other backgrounds, estimates of QED-allowed “one-photon” and “radiationless” annihilation processes of Ps^{52,53,54} suggest that careful use of low-Z materials would mitigate these decay modes, which produce energetic electrons rather than photons. The issue of radiocontamination is greatly mitigated by having a complex trigger. Rate limitations from cosmic ray muons are also significant – to avoid large dead-time losses from high-energy muons blinding the detector during trigger windows, some degree of shielding will be required. Further design studies are necessary for such an ambitious experiment.

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References

1. M. Deutsch, *Phys. Rev.* **82**, 455 (1951).
2. L. Landau, *Doklady Akad. Nauk. SSSR* **60**, 207 (1948); C.N. Yang *Phys. Rev.* **77**, 242 (1950).
3. L. Wolfenstein and D.G. Ravenhall, *Phys. Rev.* **88**, 279 (1952); L. Michel, *Nuovo Cimento* **10**, 319 (1953).
4. J.A. Wheeler, *Ann. N.Y. Acad. Sci.* **48**, 219 (1946).
5. A. Ore and J.L. Powell, *Phys. Rev.* **75**, 1696 (1949).
6. R.P. Ely and D.H. Frisch, *Phys. Rev. Lett.* **3**, 565 (1959).
7. F.A. Berends, *Phys. Lett.* **16**, 178 (1965).
8. J. Duclos *et al.*, *Phys. Lett.* **19**, 253 (1965).
9. J. Schechter, *Phys. Rev.* **132**, 841 (1963).
10. A.P. Mills and S. Berko, *Phys. Rev. Lett.* **18**, 420 (1967).
11. H.S. Mani and A. Rich, *Phys. Rev. D* **4**, 122 (1971).
12. M.I. Dobroliubov, S.N. Gninenko, A.Y. Ignatiev, and V.A. Mateev, *Int. J. Mod. Phys. A* **8**, 2859 (1993).
13. R. Escribano, E. Massó, and R. Toldrà, *Phys. Lett. B* **356**, 313 (1995).
14. V.V. Dvoeglazov, R.N. Faustov, and Y.N. Tyukhtyaev, *Mod. Phys. Lett. A* **8**, 3263 (1993).
15. G.S. Adkins, R.N. Fell, and J. Sapirstein, *Ann. Phys.* **295**, 136 (2002).
16. R.S. Vallery, P.W. Zitzewitz, and D.W. Gidley, *Phys. Rev. Lett.* **90**, 203402 (2003).
17. D.W. Gidley, A. Rich, and P.W. Zitzewitz, in *Positron Annihilation* eds. P.G. Coleman, S.C. Sharma, and L.M. Diana (North-Holland, 1982).
18. A. Rich, *Rev. Mod. Phys.* **53**, 127 (1981).
19. M.A. Strosio, *Phys. Rep.* **22**, 215 (1975).
20. M. Skalsey, *Mat. Sci. Forum* **255**, 209 (1997).

21. S.N. Ginenko, N.V. Krasnikov, and A. Rubbia, *Phys. Rev. D* **67**, 075012 (2003); S.N. Gninenko, N.V. Krasnikov, and A. Rubbia, *Mod. Phys. Lett. A* **17**, 1713 (2002).
22. S.G. Karshenboim, hep-ph/0310099 (submitted for publication).
23. S. DeBenedetti and H.C. Corben, *Ann. Rev. Nuc. Sci.* **4**, 191 (1954).
24. A. Billoire, R. Lacaze, A. Morel, and H. Navelet, *Phys. Lett. B* **78**, 140 (1978).
25. T. Muta, and T. Niuya, *Prog. Theor. Phys.* **68**, 1735 (1982).
26. G.S. Adkins and F.R. Brown, *Phys. Rev. A* **28**, 1164 (1983).
27. G.P. Lepage, P.B. Mackenzie, K.H. Streng, and P.M. Zerwas, *Phys. Rev. A* **28**, 3090 (1983).
28. S. Adachi, Bachelor thesis, Tokyo Metropolitan University, 1990.
29. S. Adachi *et al.*, *Phys. Rev. Lett.* **65**, 2634 (1990).
30. G.S. Adkins and E.D. Pfahl, *Phys. Rev. A* **59**, R915 (1998).
31. H. von Busch *et al.*, *Phys. Lett. B* **325**, 300 (1994).
32. S. Adachi *et al.*, *Phys. Rev. A* **49**, 3201 (1994).
33. J. Yang *et al.*, *Phys. Rev. A* **54**, 1952 (1996).
34. P.A. Vetter and S.J. Freedman, *Phys. Rev. A* **66**, 052505 (2002).
35. T. Matsumoto, M. Chiba, R. Hamatsu, and T. Hirose, J. Yang, and J. Yu, *Phys. Rev. A* **54**, 1947 (1996).
36. T. Nishimura *et al.*, *Appl. Surf. Science* **149**, 276 (1999).
37. K. Marko and A. Rich, *Phys. Rev. Lett.* **33**, 980 (1974).
38. M. Caravati, A. Devoto, and W.W. Repko, hep-ph/0211463.
39. D.W. Gidley *et al.*, *Phys. Rev. Lett.* **66**, 1302 (1991).
40. S. Asai *et al.*, *Phys. Rev. Lett.* **66**, 1298 (1991).
41. D. Colladay and V.A. Kostelecký, *Phys. Rev. D* **55**, 6760 (1997).
42. D. Colladay and V.A. Kostelecký, *Phys. Rev. D* **58**, 116002 (1998).
43. D. Colladay and V.A. Kostelecký, *Phys. Lett. B* **511**, 209 (2001).
44. W. Bernreuther, U. Löw, J.P. Ma, and O. Nachtmann, *Z. Phys. C* **41**, 143 (1988); W. Bernreuther, and O. Nachtmann, *Z. Phys. C* **11**, 235 (1981).
45. B.K. Arbic, S. Hatamian, M. Skalsey, J. Van House, and W. Zheng, *Phys. Rev. A* **37**, 3189 (1988).
46. S.K. Andrukhovich, N. Antovich, and A.V. Berestov, *Inst. and Exp. Tech.* **43**, 453 (2000).
47. P.A. Vetter and S.J. Freedman, *Phys. Rev. Lett.* **91**, 263401 (2003).
48. M. Felcini, *Int. J. Mod. Phys. A*, submitted for publication (2003). Proceedings of the Workshop on Positronium Physics, Zurich, 2003.
49. M. Skalsey and J. Van House, *Phys. Rev. Lett.* **67**, 1993 (1991).
50. A. Badertscher *et al.*, *Phys. Lett. B* **542**, 29 (2002).
51. A.P. Mills, Jr. and D.M. Zuckerman, *Phys. Rev. Lett.* **64**, 2637 (1989).
52. A.I. Mikhailov and S.G. Porsev, *J. Phys. B* **25**, 1097 (1992).
53. J.C. Palathingal *et al.*, *Phys. Rev. A* **51**, 2122 (1995).
54. P.M. Bergstrom *et al.*, *Phys. Rev. A* **53**, 2865 (1996).
55. J. Govaerts and M. Van Caillie, *Phys. Lett. B* **381**, 451 (1996).
56. A. Czarnecki and S.G. Karshenboim, hep-ph/9911410.
57. G.S. Atoyan, S.N. Gninenko, V.I. Razin, and Yu. V. Ryabov, *Phys. Lett. B* **220** 317 (1989).
58. T. Mitsui *et al.*, *Phys. Rev. Lett.* **70** 2265 (1993).
59. A.O. Bazarko *et al.*, *Nucl. Phys. B* **91** 210 (2001).
60. A. Piepke *et al.*, *Nucl. Phys. B* **91** 99 (2001).
61. A. Badertscher *et al.*, hep-ph/0311031.